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ADVANCED SOLAR CONCENTRATOR: EXECUTIVE SUMMARY

March 1981

Acurex Project 7740
Contract 955477
DRL 016
DRD SE004

For

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

By

Acurex Corporation
Alternate Energy Division
485 Clyde Avenue
Mountain View, California 94042

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SECTION 1

INTRODUCTION

This report summarizes the results of a 9-month technical study carried out by Acurex Corporation for JPL under contract number 955477 entitled, "An Advanced Solar Concentrator Design" and provides a bibliography for all Advanced Concentrator documentation. The effort reported herein includes the preliminary design of JPL's concept for an advanced point-focusing solar concentrator, a mass production and maintenance cost assessment of that preliminary design, a conceptual evaluation of a modified concentrator design, and the detailed design of one of the reflective elements comprising the paraboloidal reflective surface.

A sketch of the Advanced Solar Concentrator conceptual design is shown in Figure 1-1. It consists of a steerable space frame structure supporting a paraboloidal mirror glass reflector. The structure is driven in azimuth and elevation by electric actuators to align the reflector with the incoming solar radiation to obtain and maintain proper image placement in the receiver which is located at the focal point of the reflector. When coupled with a receiver/engine/generator package mounted at the focus of the paraboloid, the unit is capable of generating electricity for remote applications or as a supplement to a utility grid system.

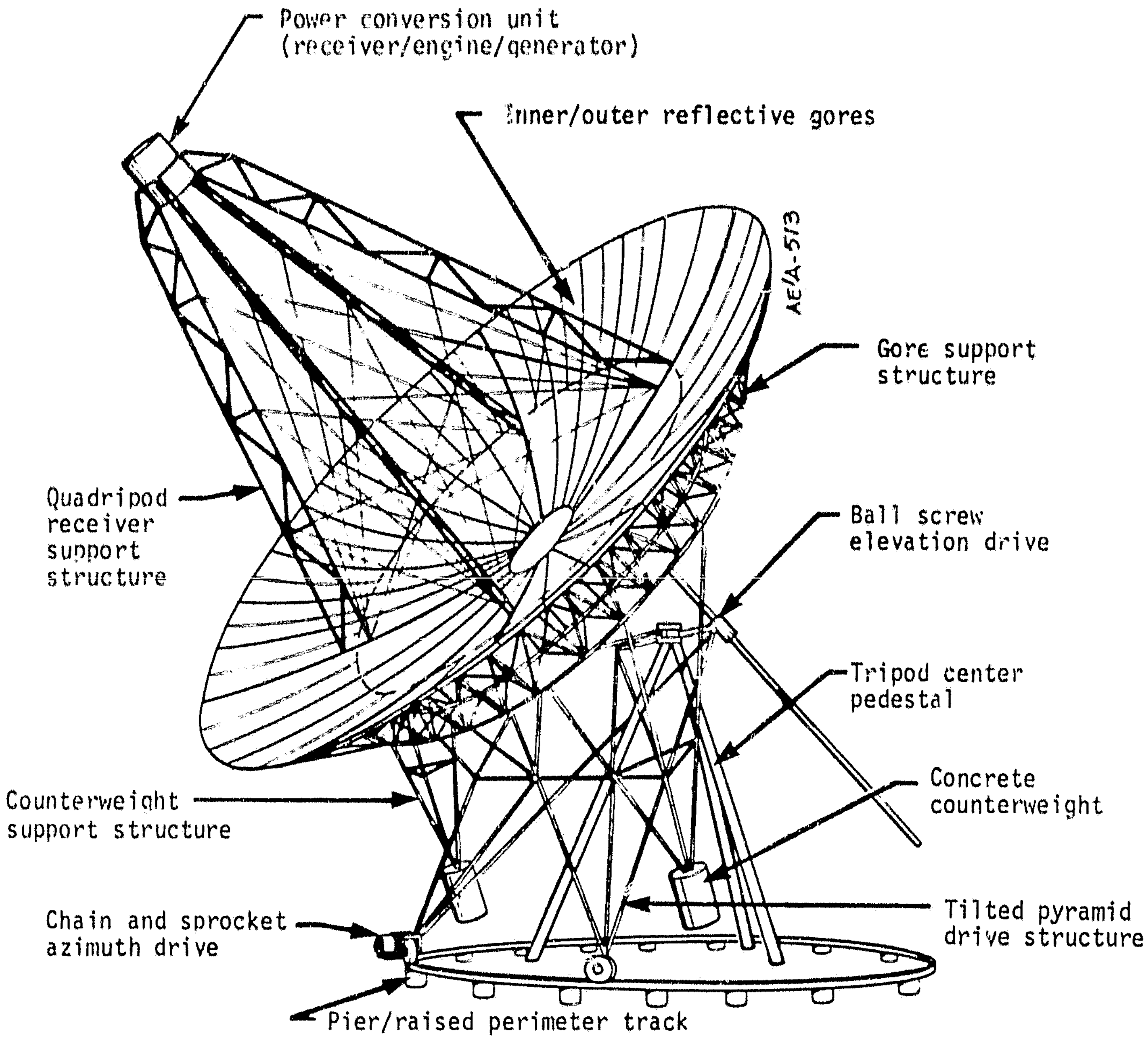

Figure 1-1. Design Description

The key feature of the Advanced Solar Concentrator is the low-cost, lightweight, self-supporting panels which make up the paraboloidal reflective surface. Each panel, or gore, is of a sandwiched construction with a thin backsilvered sheet glass front skin, a lightweight cellular glass contoured core, and a thin unsilvered sheet glass backing strip. These lightweight, structurally efficient gores allow a significant reduction in the mass of the structure, thereby reducing structure cost in mass production.

The total installed cost for the Advanced Solar Concentrator in 1975 dollars at a production level of 100,000 units per year is estimated at $10,697 per concentrator or $112.4 per square meter of gross aperture area. Proposed design modifications (Section 4) could lower this figure to $8,664 per concentrator or $91.0 per square meter. The estimated annual cost for operation and maintenance is $133 (1975 dollars) per concentrator.

The optical output of the 11 m diameter Advanced Solar Concentrator is predicted to be 64.5 kW thermal for the specified design conditions of:

- Receiver aperture diameter = 22 cm
- Insolation = 845 W/m^2
- Wind = 50 km/hr

Realistic values for reflectance, optical errors, gaps between gores, shading, and blocking as well as a representative sunshape error were used for the performance prediction.

This executive summary report is organized as follows:

- Section 2 contains a summary of the preliminary design
- Section 3 contains a summary of the mass production and maintenance cost assessment

- Section 4 contains a summary description of a modified concentrator design
- Section 5 contains a summary of the outer reflective gore detail design
- Section 6 contains a bibliography of all Advanced Solar Concentrator documentation

SECTION 2

PRELIMINARY DESIGN SUMMARY

The Advanced Solar Concentrator (Figure 1-1) is a single reflection point-focusing, two-axis tracking parabolic dish with an aperture diameter of approximately 11 m. This high performance unit is capable of achieving an average solar flux concentration in excess of 1,740 suns while operating in design winds of 50 km/hr (31 mph).

The concentrator is defined as consisting of the following five subsystems:

- Reflective surface
- Support structures
- Drive subsystem
- Foundations
- Electrical and control

A summary subsystem mass statement is provided in Table 2-1. Each of these subsystems is described in the following sections.

2.1 REFLECTIVE SURFACE

The reflective surface of the concentrator consists of two concentric rings of independent, optical quality reflective elements forming a complete, but physically discontinuous paraboloidal surface with a common focal point. As noted in Figure 1-1, two types of reflective

Table 2-1. Subsystem Mass Statement

Reflective surface	1,460 kg	(3,220 lb)
Support structures	1,965 kg	(4,327 lb)
Drive subsystem	4,995 kg*	(11,000 lb)[a]
Foundations	11,445 kg	(25,200 lb)
Electrical and control	225 kg	(500 lb)

[a]Includes 4,540 kg (10,000 lb) of reinforced concrete counterweights

elements, designated as inner and outer gores, are used to make up the reflective surface.

Each gore is installed on a ring-like gore support structure with statically determinant three-point attachments. These attachments have sufficient degrees of freedom to allow fine tuning of the composite surface geometry and to accommodate differential thermal expansion between the gores and the structure.

During preliminary design, 20 inner and 40 outer gores were selected for the structure/reflector interface. Due to glass stress limitations, however, a breakdown of 24 inner gores and 40 outer gores was selected during the detailed design effort as the best interface configuration. Since only the design of the outer gore was carried through detailed design, all discussions relative to the balance of the concentrator (structure, drives, foundations, etc.) are based on the preliminary 20/40 gore interface.

The preliminary analysis and design of the gores resulted in a lightweight, structurally rigid reflective element that is largely self-supporting. Over 35 percent of the outer gore area is overhung beyond its outermost support point.

As shown in Figure 2-1, each gore is fabricated from a composite of 1.0 mm (0.040 in.) Corning Glass Works 7809 borosilicate glass and a Pittsburgh Corning Foamsil® 75 cellular glass core. The Foamsil® 75 has been specially formulated to match the thermal expansion characteristics of the 7809 sheet glass. A single sheet of backsilvered thin glass is continuously bonded to a contoured substrate of the cellular glass material. A narrow strip of unsilvered thin glass is bonded to the face of the cellular glass spar running longitudinally along the backside of the gore. The face sheets and the cellular glass core form a composite structure in which the mirror glass and the spar cap carry the majority of the bending loads while the core material carries the shear loads.

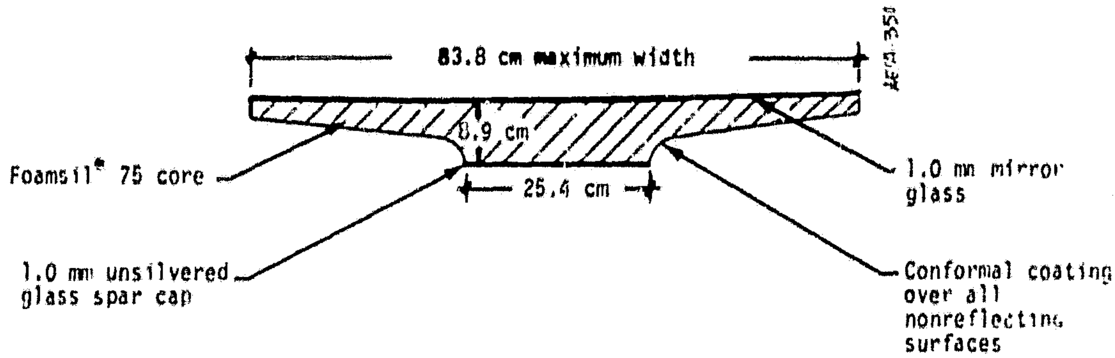

Figure 2-1. Reflective Element Cross Section

Near-term fabrication techniques will require an initial bonding of standard sized cellular glass blocks to form a large slab which will subsequently be machined to form the desired planform and contour of the core. The mirrored and unsilvered glass sheets will then be bonded to the core along with the attachment hardware, and all nonreflective surfaces coated with a weatherproof conformal coating.

The key physical properties of the gore design at the preliminary design level are summarized in Table 2-2.

Table 2-2. Preliminary Gore Design Summary

	Outer Gore	Inner Gore
Length, cm (in.)	229 (90)	269 (106)
Maximum width, cm (in.)	84 (33)	99 (39)
Number required/concentrator	40	20
Mass (bare gore), kg (lb)	23 (51)	17 (38)
Mass (with attachment pads), kg (lb)	26 (58)	20 (45)
Sizing criteria	Stress limit	Slope error limit
Sizing wind speed, km/hr (mph)	110 (68)	50 (31)
Accumulated exposure in 30 yr	1 min	--
Maximum deflection slope error, mrad[a]	0.22	0.38
Approximate rms deflection slope error, mrad[a]	0.17	0.24[b]
Maximum deflection, cm (in.)[a]	0.0127 (0.005)	0.0305 (0.012)

[a]50 km/hr (31 mph) wind speed, uniform pressure, $C_p = 3.3$
[b]Used for preliminary performance calculations

2.2 SUPPORT STRUCTURES

The concentrator support structure serves three functions: (1) interfacing between the receiver/engine/generator package, or power conversion module (PCM), the drive subsystem, the reflective surface, and the foundations; (2) providing a rigid support of the required subsystems; and (3) providing an articulated two-axis tracking capability. To provide the required rigidity while meeting the low-weight design goal,

structurally efficient steel space frame structures were designed. The structure subsystem is comprised of the following subassemblies:

- Gore support ring structure
- Drive structure
- Counterweight structure
- Receiver/engine support structure
- Pedestal

Each of these subassemblies is described in the following paragraphs.

Gore Support Structure

The gore support structure is a steel space frame ring supporting the 60 gore elements and interfaces with the receiver support structure, the elevation drive mechanism and bearings, and the counterweight support structures. Gore support ring deflections translate directly into lower concentrator performance due to the reduction in optical concentration resulting from the rigid body rotation of the gores. The support ring design has therefore been optimized to provide the best balance between stiffness and structure weight.

The gore support structure consists of a truss-like ring with tripod "outriggers." Each gore is supported at the tip of an outrigger and at two points on the central ring. The gore support structure has been carefully designed to minimize midspan loading of members thereby maximizing structural efficiency.

Drive Structure

The drive structure serves as an intermediate structure between the reflector assembly, the center pivot pedestal, and the azimuth drive. It also makes use of the space frame concept to maximize structural efficiency. The drive structure is pivoted about the azimuth axis at the

top of the pedestal. Loads are transmitted to the pedestal through the azimuth bearing and to the track through the azimuth drive unit and idler wheels located at the lower corners of the drive support structure.

The drive structure geometry was carefully analyzed to select a configuration providing a good balance between actuator loads, structural weight, and concentrator motion limits.

Counterweight Structure

The counterweight structure is a simple tubular steel space frame providing a structural interface between the precast concrete counterweights and the gore support ring. Two mirror image counterweight structures are required per concentrator.

Receiver/Engine Support Structure

The receiver/engine support structure is a guyed quadripod with flat truss legs designed to provide the required strength and rigidity while minimizing optical losses due to shadowing and blockage. The receiver mounting flange and sleeve located at the quadripod apex do not make use of the receiver housing as a load-carrying member.

Pedestal

The center pivot pedestal is a simple tubular steel tripod. The pedestal supports the azimuth bearing and provides the structural load path to react the loads transmitted through the bearing. Since no significant moments can be transmitted through the azimuth bearing, the simple tripod design provides the most efficient structural configuration. The mass of each structural subassembly is summarized in Table 2-3.

Table 2-3. Structural Design Summary

Description of Structure	Mass of Structure kg (lb)
Gore support ring	658 (1,450)
Drive structure	590 (1,300)
Counterweight structure	154 (340)[a]
Receiver/engine support structure	253 (557)
Pedestal	154 (340)

[a]Each structure (two required per concentrator)

2.3 DRIVE

The drive subsystem provides power and activation for solar tracking and for emergency stow and desteer. An elevation over azimuth two-axis tracking drive scheme was a basic feature of the JPL design concept. Various drive design options were carefully evaluated to select the most cost-effective means of providing the required azimuth/elevation motions.

Both hydraulic and electric actuators were considered. An all-electric approach was selected primarily due to the backup emergency stow requirement in the event of a grid power failure. The required power is provided by a gasoline motor-generator set.

The selected elevation drive incorporates an electrically driven ball screw actuator with an automatic motor brake to prevent unpowered backdriving of the unit. The actuator uses a fixed screw with a driven nut. The motor, reduction unit, and drive nut are mounted in a support yoke at the top rear end of the drive support structure. Accordian boots

provide environmental protection of the screw to minimize maintenance requirements.

The azimuth drive consists of an electrically driven chain and sprocket unit. The motor, gear reduction unit, and drive sprocket are mounted to one of the drive structure support legs with the chain being anchored to the elevated track. The chain is housed in a steel channel with flexible rubber closures to minimize environmental contamination. Due to the mechanical advantage afforded by the perimeter drive scheme, very low azimuth backlash can be achieved with relatively low chain tensioning requirements. The high longitudinal stiffness to lateral flexibility ratio of a chain makes it the preferred choice when compared to similar perimeter drive schemes employing cables. Azimuth drive maintenance costs will be minimized through the use of the environmental enclosures and the relatively slow rate at which the unit will be operated.

The key features of the drive subsystem components are summarized in Table 2-4.

2.4 FOUNDATION

The concentrator foundation subsystem includes the three reinforced concrete piers supporting the center pivot pedestal structure, the 12 reinforced concrete piers supporting the raised steel perimeter track, and the track itself. Given that a perimeter track is required (it is basic to the JPL concept), the raised steel/concrete pier configuration provides the lowest life-cycle cost and the greatest flexibility for varied terrain and soil conditions.

The key features of the foundation components are summarized in Table 2-5.

Table 2-4. Drive Component Summary

• Elevation drive	
-- Ball screw	90 kN (10-ton capacity) 5.72 cm (2.25 in.) diameter screw 6.1 m (20 ft) stroke
-- Gear box	18:1 ratio 5.65 N-m (800 in.-oz) output
-- Motor	1750 rpm 0.75 kW (1 hp) Permanent split capacitor
• Azimuth drive	
-- Chain	2.54 cm (1 in.) pitch No. 80 roller
-- Drive sprocket	30 cm (12 in.) pitch diameter
-- Gear box	100:1 ratio 1,500 N-m (1,100 ft-lb) output
-- Motor	72 rpm 0.12 kW (1/6 hp) Permanent magnet stepper
• Emergency power unit	
-- Generator	6.5 kW, 208V, three-phase, 60-cycle, gasoline-powered
-- Transfer switch	30A, 400V, three-phase, four-wire

Table 2-5. Foundation Design Summary

Track	Full circle divided into six arc segments 17.8 x 7.62 x 0.48 cm wall (7 x 3 x 3/16 in.) structural steel tubing 4.1 m (13 ft, 4-1/2 in.) inside diameter
Track piers	12 piers required Reinforced concrete 0.3 m (1 ft) diameter 3.0 m (10 ft) deep
Pedestal piers	Three piers required Reinforced concrete 0.3 m (1 ft) diameter 4.1 m (13 ft 4 in.) deep

2.5 ELECTRICAL AND CONTROL

The electrical subsystem consists of off-the-shelf components for power distribution, overload protection, and lightning protection. A separate utility fed circuit is provided for the tracker control unit and the drive subsystem. Fused disconnects protect all circuitry with separate motor starters for the azimuth and elevation drive motors.

The receiver support structure legs were sized to serve the combined function of electrical conduits in addition to their structural roles. Flexible weatherproof cabling is provided for the power circuits at the azimuth and elevation bearings.

A conventional lightning protection system employing structure mounted lightning arrestors and a dedicated grounding path is provided for incorporation in lightning susceptible areas.

The major electrical subsystem components are summarized in Table 2-6.

Table 2-6. Electrical Subsystem Component Summary

Quantity	
1	100-amp disconnect switch
1	100-amp fused disconnect switch
1	30-amp fused disconnect switch with motor starter
1	30-amp fused disconnect switch
1	Single pole starter size 00
2	Lightning arresters
2	Ground rods and accessories

The tracker/control subsystem is a microprocessor-based hybrid unit incorporating synthetic (ephemeris) and active (optical) tracking schemes. Each concentrator will be furnished with a self-contained

tracker/control unit. Ephemeris tracking, provided by the microprocessor in conjunction with precision positional feedback potentiometers, maintains gross concentrator alignment and incorporates safe desteer and sun acquisition schemes. An image sensing optical sensor provides fine tuning override signals to maintain an accurate focus during high insolation periods.

The tracker control unit accepts external receiver malfunction desteer commands and high wind stow commands overriding the normal tracking functions.

The key features of the tracker/control subsystem are summarized in Table 2-7.

Table 2-7. Control Subsystem Component Summary

Tracker computer	Two-axis hybrid system -- microcomputer-based with built-in clock and battery backup
Tracker photodetector	Multielement photobalancing apparatus located to monitor reflected flux on receiver
Positional feedback transducers	Absolute digital shaft encoders or potentiometers for azimuth and elevation angular position information
Interconnection hardware	Cabling, conduit, connection boxes, etc.
Control interfacing equipment	Supplied with computer for control/data acquisition

SECTION 3

MASS PRODUCTION, OPERATION AND MAINTENANCE COST ASSESSMENT

The objective of this assessment was to estimate the production, installation, operations and maintenance costs of the Advanced Solar Concentrator preliminary design at:

- Production rates of 10^2, 10^3, 10^4, 10^5 and 10^6 concentrators per year
- Concentrator aperture diameters of 5, 10, 11, and 15 meters
- Various receiver/power conversion package weights.

The objective of this cost assessment effort was accomplished using a "bottom up" or detailed costing approach. The cost elements making up the total installed concentrator cost and operations and maintenance costs were broken down in detail. This costing approach provides a high level of accuracy as each estimate is made for a detailed cost element of the concentrator.

A key part of the cost analysis approach was using qualified subcontractors to provide "real-world" cost estimates for those elements of the concentrator for which there existed related experience. Pioneer Engineering and Manufacturing Company of Warren, Michigan provided the cost estimates for production of the structure and drive components. Pioneer has extensive related experience in costing high production rate manufactured parts. Newbery Constructors Inc. of Phoenix, Arizona

provided the cost estimates for installation of the concentrator. Newbery has extensive general site work and construction experience with specific related experience in the field erection of transmission towers which are large space frame structures like point focus solar concentrators are.

For purposes of this mass production cost analysis, cost is defined as the cost of merchandise plus the amortized cost of capital equipment. Typical business expenses which are not included as cost in this assessment are selling, research and development, general and administrative, interest, and income tax expenses. Profit is also not included. Detailed cost estimates were made in 1980 dollars and scaled back to 1978 and 1975 dollars, using appropriate scaling factors at the summary level only.

Caution must be emphasized about comparing cost estimates made by different analysts; whether they are for identical or different system designs -- they cannot be compared with any certainty -- underlying cost assumptions made by the cost analyst may totally dictate the quantitative cost estimate. Comparison of cost estimates of competing designs, for example, should only be made when a single unbiased analyst has performed a side-by-side cost analysis employing a totally consistent set of assumptions.

The total installed cost for the Advanced Solar Concentrator in 1975 dollars is estimated at $10,697 or $112.4 per square meter of gross aperture area. A summary of the cost by major cost breakdown element is presented in Table 3-1.

These costs have been developed based on conceptual level production, shipping, and installation plans as described in the following paragraphs.

Table 3-1. Advanced Concentrator Cost Summary
(per concentrator at 10^5 units/yr, 11 m aperture)

Cost Element	1980 $	1978 $		1975 $	
	$/conc	$/conc	$/m^2	$/conc	$/m^2
Production Costs					
1000 Reflective Panels	3,905	3,254	34.3	2,616	27.5
2000 Drives	1,353	1,127	11.9	907	9.5
3000 Electrical and Control	917	764	8.0	614	6.5
4000 Structure	2,868	2,390	25.2	1,922	20.2
5000 Factory Assembly	228	190	2.0	153	1.6
Total Factory Costs	9,271	7,725	81.3	6,212	65.3
6000 Shipping	962	801	8.4	645	6.8
Installation Costs					
7000 Installation					
7100 Site Preparation	1,762	1,265	13.3	1,181	12.4
7200 Foundation Installation	2,870	2,061	21.7	1,923	20.2
7300 Site Assembly	1,098	809	8.5	736	7.7
	5,730	4,135	43.5	3,840	40.3
Total Installed Costs	$15,963	$12,661	$133.3	$10,697	$112.4
Operations and Maintenance Costs					
8000 Operations and Maintenance					
8100 Operations	8/yr	7/yr	0.07/yr	5/yr	0.05/yr
8200 Scheduled Maintenance	159/yr	133/yr	1.40/yr	107/yr	1.13/yr
8300 Unscheduled Maintenance	32/yr	27/yr	0.28/yr	21/yr	0.22/yr
Total O&M Costs	$199/yr	$167/yr	$1.75/yr	$133/yr	$1.40/yr

The conceptual production approach developed for the Advanced Solar Concentrator at the 100,000 per year production rate is as follows:

- Reflective Panels -- The reflective panels are assembled from purchased glass components. This is accomplished in a single plant located adjacent to a glass manufacturing plant. The finished panels are shipped to regional final assembly facilities located near the solar energy system installation sites.
- Drives, Electrical, and Control -- These components are purchased parts. They are shipped by the vendors to the regional final assembly facilities. In actual implementation, these parts may be made in-house, but within the scope of this study, it was decided to rely on vendor quotes to provide cost estimates. It is anticipated that the economics would not be significantly different for in-house manufacture at the 100,000 units per year production rate.
- Structure -- The structure subassemblies of the concentrator are fabricated at regional plants of approximately 20,000 units per year capacity. These plants are to be located close to the areas in which the concentrators will be installed. These regional structural steel fabrication plants are colocated with the concentrator final assembly facilities.
- Final Assembly -- The various elements of the concentrator are assembled at the regional final assembly plant, located next to the structure fabrication facility. In this facility the concentrator is virtually fully assembled, before airshipping

to the installation site. All elements which attach to the pedestal (structure, reflective panels, drives, controls) are assembled in the factory to save on expensive field labor.

The shipping approach is shipping fully assembled concentrators (except for the pedestal and track) to the site by air (airship or heliocopter). By using airshipping, field assembly labor is kept to a minimum and total installed cost is reduced.

The installation costs are estimated to be $3,840 (1975 dollars) per concentrator. The installation element encompasses site preparation, foundation installation and site assembly costs. With the airshipping approach, installation costs are 33 percent of the total installed concentrator cost. With common carrier shipping and site assembly of piece parts, the installation cost element would be approximately 50 percent of the total installed cost. Airshipping was selected because it provided the lowest total installed concentrator cost.

The operations and maintenance costs are estimated to be $133 (1975 dollars) per concentrator per year.

Costs were scaled as a function of production rate, aperture diameter, and receiver weight from the cost estimates developed in the detailed effort (at 11 meter diameter, 10^5 units per year and 1350 kg receiver/power conversion weight). The results shown in Figure 3-1 quantify the cost reductions possible through the economics of high production rates and show that 11 meters is the minimum cost aperture size for this particular design concept. Significant changes in receiver/power conversion weights had only a small impact on installed concentrator costs.

The preliminary design is only one iteration in the evolution of an Advanced Solar Concentrator; therefore, the cost analysis presented in

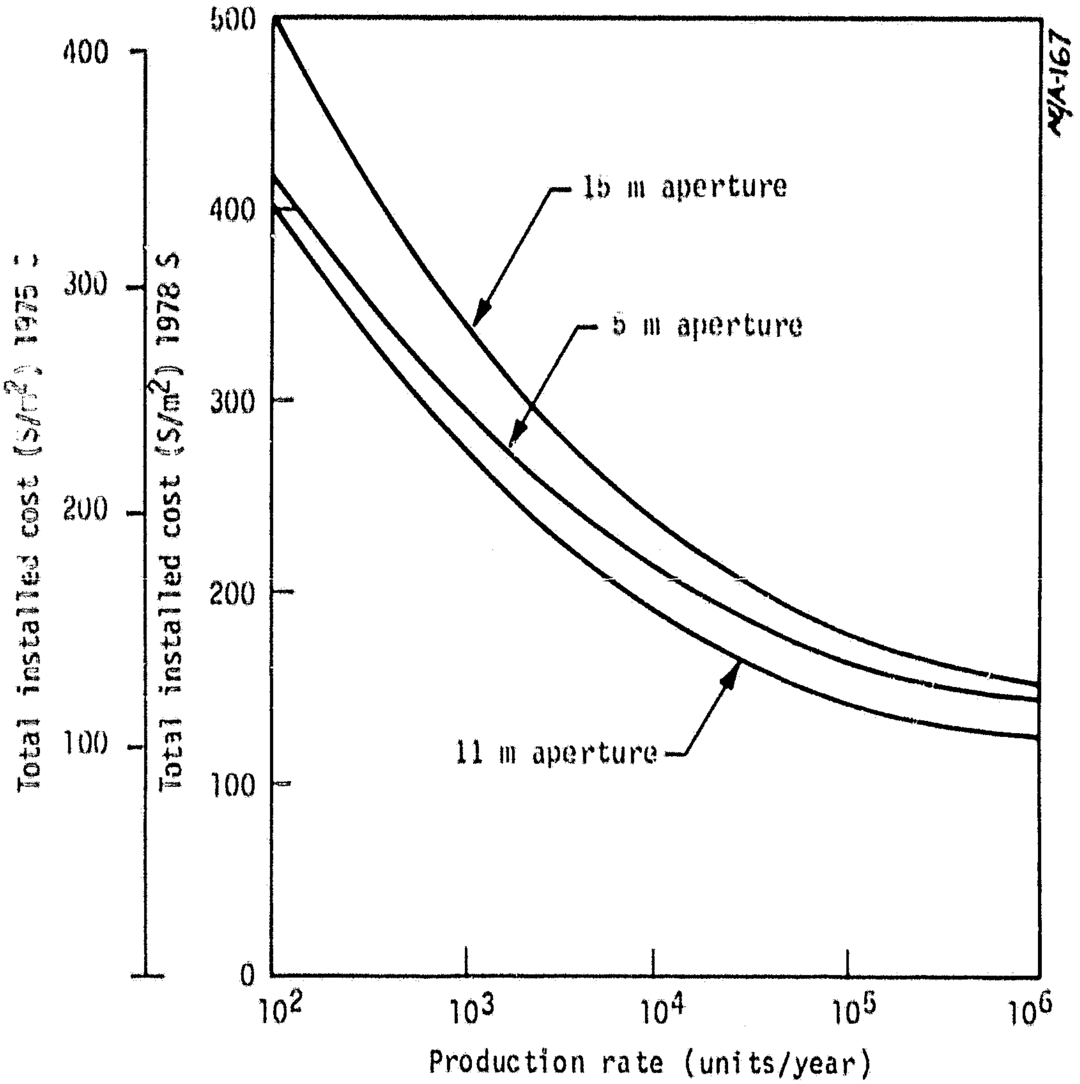

Figure 3-1. Cost Scaling Results

this report only indicates where effort should be expanded to achieve cost reductions rather than providing absolute and nonchanging values. Over the course of our design and cost analysis efforts we have identified a number of potential cost reduction areas. The major cost reductions can be categorized as follows:

- Specification Requirements -- Operational and survival wind loads are major drivers in the design of virtually all components of the concentrator. The probability of encountering the governing wind loads is extremely low, and can be reduced by using wind screens and accounting for mutual wind blocking.
- Concept Redesign -- Two areas of redesign that can significantly reduce the installed cost of the system are the mount and foundation assembly and the counterweight assembly. The collector mount includes all strucutral components between the foundation and the gore supporting. While the wide base perimeter mount system provides the lightest weight concentrator, it requires significant site preparation and foundati ., installation labor. A more material intensive design using a single pedestal mount allows for low cost site preparation and foundation installation and would most likely result in a lower total installed cost. Counterweight systems, although allowing for reduced elevation drive motor requirements and low parasitic operating power, result in higher life cycle cost concentrators than noncounterweighted systems.

- Materials Technology -- Two areas of material technology development have the potential for reducing the cost of the critical reflective panel component. A full size monolithic cellular glass core formed to rough contour would eliminate the 50 percent of the material required and the labor operations of bonding and trimming multiple small size cellular glass blocks. The development of large, high strength temperable mirror glass sheets would allow wider reflective panels, and therefore, fewer panels per concentrator with the attendant reductions in attachment hardware, supporting structure and the number of individual alignment operations.

SECTION 4

MODIFIED CONCENTRATOR DESIGN SUMMARY

The cost assessment of the Advanced Solar Concentrator preliminary design (Section 3) identified two areas of redesign that offered the potential for a significant reduction in total installed cost without affecting optical performance. The two areas of redesign are: (1) substituting a single pedestal mount, single pier foundation for the original wide base perimeter mount, raised track on multipier foundation; and (2) eliminating the counterweight assembly.

The Advanced Solar Concentrator design, modified to incorporate these design changes is depicted in Figure 4-1. The total installed cost in 1975 dollars at a production level of 100,000 units/yr is estimated at $8,664 per concentrator or $91 per square meter of gross aperture area, a 19 percent reduction from the original design concept.

The effects of each design modification are described below.

4.1 MOUNT AND FOUNDATION REDESIGN

The single pedestal mount, single pier foundation concept results in a lower total concentrator installed cost than the wide base carousel mount, raised track, multi-pier foundation concept. While the mass of the mount structure must be increased to carry the loads from the panel support structure to the central pedestal, the single pedestal weight allows for reduced site preparation and foundation installation material

Figure 4-1. Modified Concentrator Design Description

and labor. The site preparation and foundation installation cost reductions more than offset the increase in structural steel cost, thereby reducing total installed cost.

The primary cost reductions attributable to the single pedestal mount, single pier foundation are as follows:

- Reduced site grading requirements -- The site does not need to be graded to the same degree of precision that it would for a wide base perimeter type foundation
- Reduced surveying requirements -- The single pier foundation need only be approximately located whereas the wide base foundation concept requires the accurate location of many piers
- Reduced setup time for drilling holes, placing forms and rebar, and pouring concrete
- Elimination of the fabrication, shipping, and assembly of the curved steel track

4.2 ELIMINATION OF COUNTERWEIGHT ASSEMBLY

Elimination of the counterweight assembly results in a savings in material and labor for fabrication and assembly. The counterweight assembly consists of 4.540 kg (10,000 lb) of concrete ballasts and 308 kg (680 lb) of tubular steel space frame. This assembly must be fabricated, then shipped to the site and assembled. While its elimination results in higher elevation drive motor requirements and higher operating parasitic power, the life cycle cost of delivered energy for a noncounterweighted concentrator design is significantly reduced.

SECTION 5

OUTER REFLECTIVE GORE DETAILED DESIGN SUMMARY

The detailed design task included the design of the outer reflective gore element and a final evaluation of the concentrator's thermal performance. The outer gore assembly drawing is shown in Figure 5-1.

The outer gores consist of a wedge-shaped cellular glass structural core whose thickness varies laterally from a central maximum to the edge. A central spar runs full length along the rear surface of the gore to provide bending stiffness. A full area backsilvered glass face sheet is bonded to the paraboloidal front surface of the gore and a clear glass cap is bonded to the central spar, forming a skin-stressed composite structure with a high structural efficiency. The center thickness of the cellular glass core is 8.4 cm (3.5 in.) including the spar. The gores use a single full-sized face sheet of silvered Corning 7809 glass, 1.0 mm (0.040 in.) thick, adhesively bonded to the contour of the paraboloid. A 25.4 cm (10-in.) wide piece of 1.0-mm (0.040-in.) unsilvered 7809 glass is bonded to the surface of the cellular glass spar with the same resin system. The glass and Foamsil® form a composite structure in which the mirror and spar cap glass carry the bending load while the core material carries the shear load.

Figure 5-1. Outer Gore Assembly Drawing

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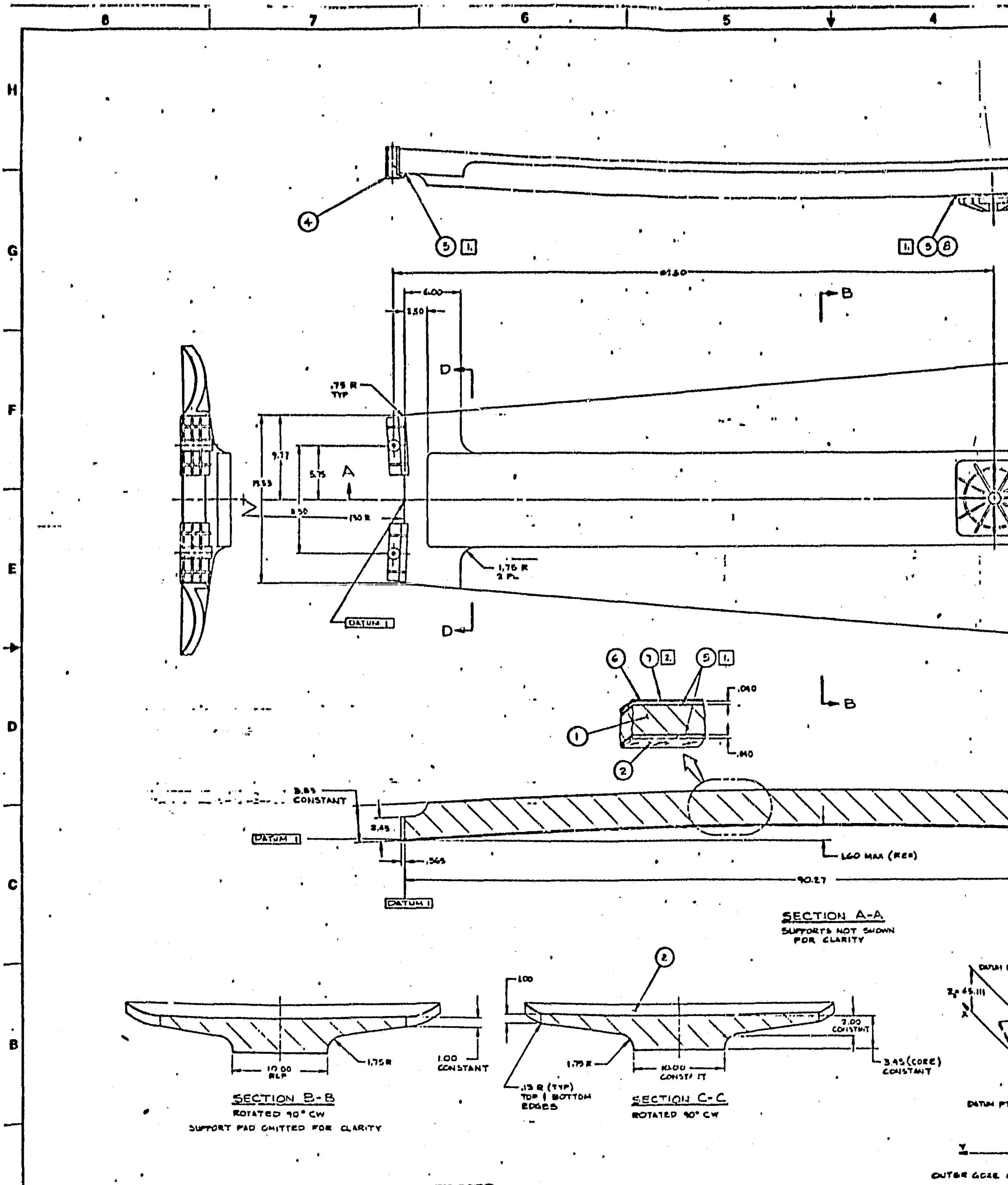

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FOLDOUT FRAME

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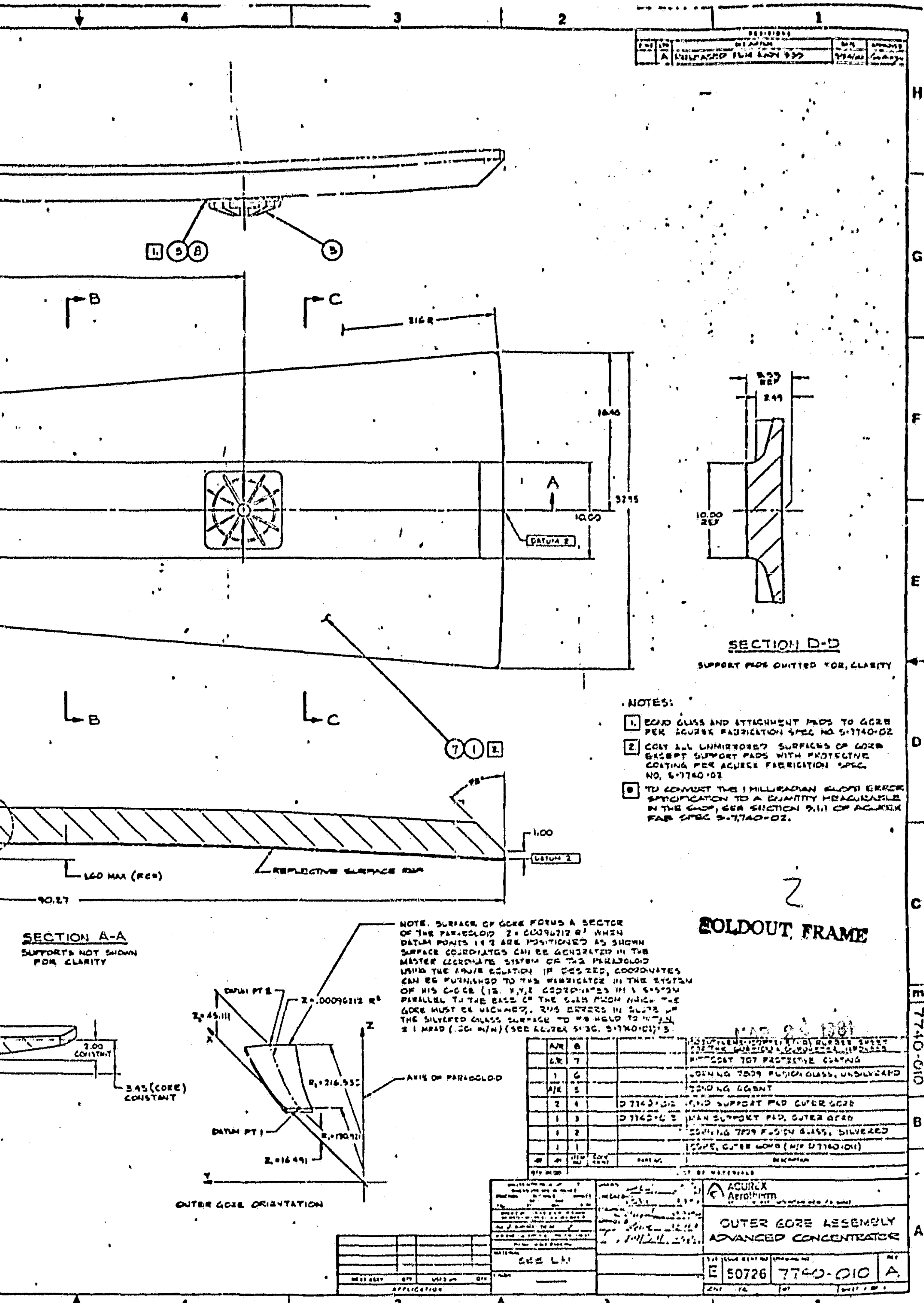

REVISIONS
A RELEASED PER ECN 930
SECTION D-D
SUPPORT PADS OMITTED FOR CLARITY
NOTES:
1. BOND GLASS AND ATTACHMENT PADS TO GORE PER ACUREX FABRICATION SPEC NO. 5-7740-02
2. COAT ALL UNMIRRORED SURFACES OF GORE EXCEPT SUPPORT PADS WITH PROTECTIVE COATING PER ACUREX FABRICATION SPEC. NO. 5-7740-02
3. TO CONVERT THE 1 MILLIRADIAN SLOPE ERROR SPECIFICATION TO A QUANTITY MEASURABLE IN THE SHOP, SEE SECTION 9.1.1 OF ACUREX FAB SPEC 5-7740-02.
DATUM 2
10.00
10.00 REF
REFLECTIVE SURFACE DIM
1.60 MAX (REF)
1.00
90.27
SECTION A-A
SUPPORTS NOT SHOWN FOR CLARITY
2.00 CONSTANT
3.45 (CORE) CONSTANT
NOTE. SURFACE OF GORE FORMS A SECTOR OF THE PARABOLOID Z = .00096212 R² WHEN DATUM POINTS 1 & 2 ARE POSITIONED AS SHOWN. SURFACE COORDINATES CAN BE GENERATED IN THE MASTER COORDINATE SYSTEM OF THE PARABOLOID USING THE ABOVE EQUATION. IF DESIRED, COORDINATES CAN BE FURNISHED TO THE FABRICATOR IN THE SYSTEM OF HIS CHOICE (IE. X,Y,Z COORDINATES IN A SYSTEM PARALLEL TO THE BASE OF THE SLAB FROM WHICH THE GORE MUST BE MACHINED). RMS ERRORS IN SLOPE OF THE SILVERED GLASS SURFACE TO BE HELD TO WITHIN ± 1 MRAD (.001 IN/IN) (SEE ACUREX SPEC. 5-7740-02) 3
DATUM PT 2
Z = .00096212 R²
Z₂ = 45.111
R₂ = 216.937
AXIS OF PARABOLOID
DATUM PT 1
R₁ = 130.91
Z₁ = 16.491
OUTER GORE ORIENTATION
FOLDOUT FRAME
MAR 24 1981
QTY	ITEM NO	PART NO.	DESCRIPTION
A/R	8		SUBSTITUTE (OPTIONAL) RUBBER SHEET FOR THE CURING COMPOUND
A/R	7		PITTSBURGH 707 PROTECTIVE COATING
1	6		CORNING 7809 FUSION GLASS, UNSILVERED
A/R	5		BONDING AGENT
2	4	D 7740-012	END SUPPORT PAD OUTER GORE
1	3	D 7740-013	MAIN SUPPORT PAD, OUTER GORE
1	2		CORNING 7809 FUSION GLASS, SILVERED
1	1		CORE, OUTER GORE (M/F D7740-011)
LIST OF MATERIALS
ACUREX Aerotherm
OUTER GORE ASSEMBLY ADVANCED CONCENTRATOR
E 50726 7740-010 A
SEE L.M.

Attachment to the ring truss is accomplished through glass fiber reinforced polyester pads containing threaded metal inserts for attachment of support linkage. The pads are bonded to the gore with an elastomeric adhesive system. After glass and attachment pads are bonded to the gore, a protective coating is applied to all unmirrored areas of the gore to protect the cellular glass core and mirror edge from the environment.

Performance analyses conducted during the preliminary design effort were based on an assumed rms manufacturing slope error for the gores of 3.0 mrad. Due to the unproven nature of using cellular glass as a structural substrate for reflective panels, the 3.0 mrad maximum specified value was conservatively assumed. This relatively poor surface accuracy led through the optimization trade-offs to a deflection limited structural design with an optimum aperture diameter of 10.9 m.

Concurrent work at JPL in the fabrication of reflective panel elements for the Test Bed Concentrator indicated that manufacturing slope errors of 1.0 mrad or less were achievable with cellular glass substrates. The concentrator performance was therefore reevaluated with a 1.0-mrad gore manufacturing slope error and updated gore deflection slope errors as determined during detailed design. The results are presented in Table 5-1.

The results are presented for an 11.0-m diameter concentrator (the baseline design). Due to the higher accuracy of the gores, the structural stiffness can be relaxed to the point where the structure becomes stress limited. The performance impact of increased gore accuracy far outweighs the effects of reduced structural stiffness. The optical output of the concentrator is increased from 56 kW for the optimized 10.9-m concentrator with the 3.0-mrad gores to 64.5 kW for a stress-limited 11.0-m

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Table 5-1. Final Performance Summary

Design Conditions	
Insolation	$I = 0.845$ kW/m^2
Sunshape error	$\sigma_{SS} = 3.07$ mrad
Wind	$W = 50$ km/hr
Collector rim angle	$\theta = 45^{\circ}$
Receiver aperture diameter	$D_r = 22$ cm
Concentrator Parameters	
Concentrator diameter	$D_c = 11.0$ m
Convolved error cone	$\sigma^* = 4.31$ mrad
Specularity	$\sigma_W = 0.25$ mrad
Structural deflection	$\sigma_d = 1.90$ mrad
Gore slope error	$\sigma_s = 1.00$ mrad
Gore deflection	$\sigma_g = 0.132$ mrad
Reflectance	$\rho = 0.94$
Gap loss coefficient	$K_G = 0.919$
Shading loss coefficient	$K_S = 0.998$
Blocking loss coefficient	$K_B = 0.989$
Pointing error	$E_p = 1.7$ mrad
Results	
Optical energy at receiver aperture	$E = 64.5$ kW
r/D	$r/D = 0.0100$
Intercept factor	$\phi = 0.938$

concentrator with the 1.0-mrad gores. While 2 percent of this increase comes from the diameter change, the remaining 13 percent is a result of the gore and structure changes.

The sensitivity of concentrator performance to gore slope error, wind speed, and pointing error was also determined. As shown in Figure 5-2, for an 11.0-m stress-limited concentrator design, concentrator performance is relatively insensitive to wind speed for gore manufacturing slope errors less than 1.0 mrad. The performance increase from the 50-km/hr design point to a zero wind speed condition is less than 5 percent for the 1.0-mrad gore whereas it is roughly 10 percent for a 3.0-mrad gore. Reductions in gore manufacturing slope error below the 1.0-mrad point can also be seen to be of little benefit.

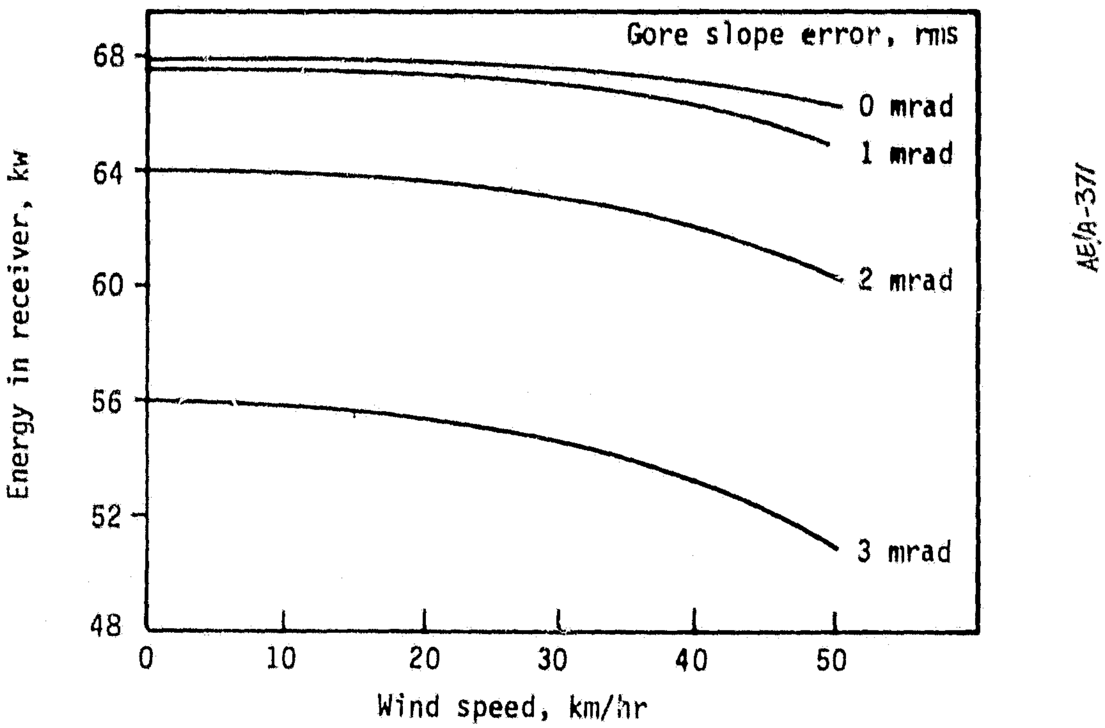

Figure 5-2. Effects of Wind Speed and Gore Slope Error Upon Collector Performance

Figure 5-3 presents the performance sensitivity of the concentrator to pointing error. As can be seen from the figure, less than 1 percent of the energy is lost due to pointing errors below the 1.75-mrad specified value. Pointing error becomes a significant factor at values much beyond this point, however.

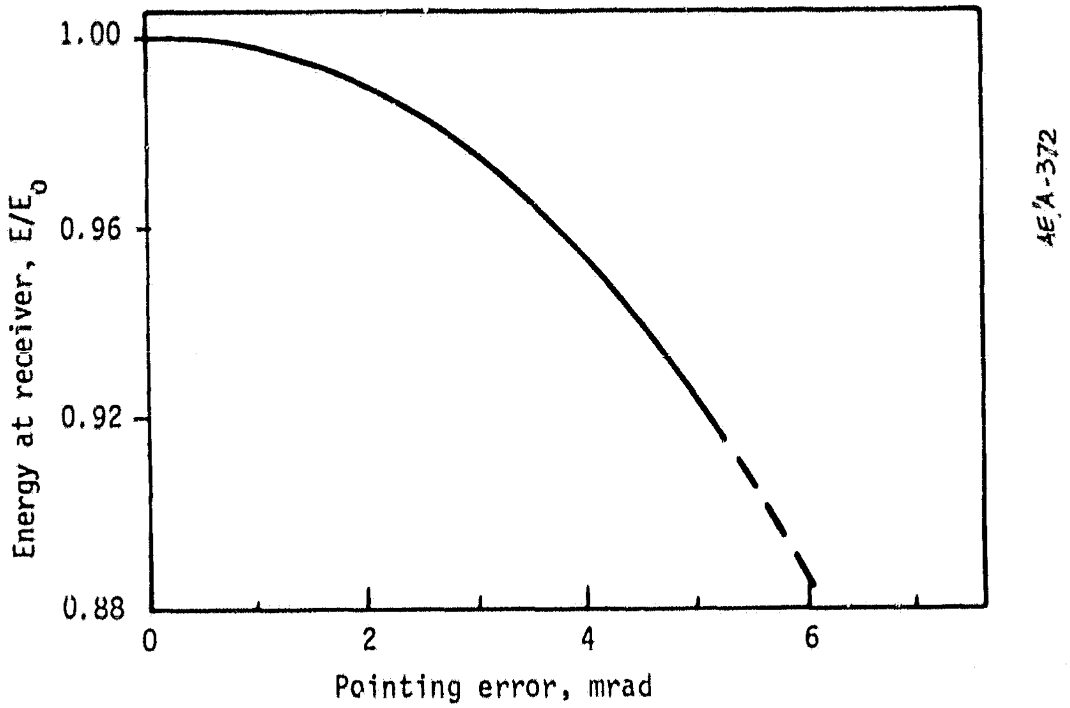

Figure 5-3. Concentrator Sensitivity to Pointing Errors

SECTION 6

BIBLIOGRAPHY

All Advanced Solar Concentrator documentation is contained in the following two final reports:

- "Advanced Solar Concentrator Preliminary and Detailed Design," Acurex Final Report FR-80-16/AE, dated January 1981
- "Advanced Solar Concentrator Mass Production, Operation and Maintenance Cost Assessment," Acurex Final Report FR-80-14/AE, dated January 1981

This section contains a bibliography of the information presented in the above-mentioned reports.

6.1 ACUREX FINAL REPORT FR-80-16/AE

This report has been organized to follow the division of work between the preliminary design and the outer gore detailed design to the greatest extent possible. Section 1 contains an introduction and summary. The preliminary design is discussed fully in Section 2, while Section 3 presents the results of the detailed design effort.

To aid the reader, the Advanced Solar Concentrator design as it stood at the completion of the preliminary design effort is described in detail in Section 2.1. Pertinent subsystem characteristics are summarized in this section. The balance of Section 2 then presents the discussion of the trade-off and analysis leading to this design.

Several appendices have been provided. They include:

- Appendix A -- "Design Requirements, Specification, and Definition for a Point-Focusing Advanced Solar Concentrator" (Exhibit I of JPL Contract 955477)
- Appendix B -- "Preliminary Design Basis and Requirements for an Advanced Point-Focusing Solar Concentrator" (Acurex Specification Number S-7740-01, Revision A)
- Appendix C -- "Preliminary Hazards Analysis (PHA) for the Advanced Point-Focusing Solar Concentrator"
- Appendix D -- "JPL Advanced Concentrator Preliminary Drawing Package"
- Appendix E -- "JPL Advanced Concentrator Outer Gore Detailed Drawing Package"
- Appendix F -- "Prototype Fabrication Specification for a Reflective Element (Gore) of an Advanced Point-Focusing Solar Concentrator" (Acurex Specification Number S-7740-02)
- Appendix G -- "Cellular Glass Gore Test Plan"

6.2 ACUREX FINAL REPORT FR-80-14/AE

This report has been organized to follow the cost breakdown structure. Section 1 presents an introduction and summary, while Section 2 provides the cost methodology. The next four sections contain the detailed cost results as follows:

- Section 3 PRODUCTION PLAN

  3.1 Overall Production Approach
  3.2 Reflective Panels Production Plan
  3.3 Purchased Parts
  3.4 Structural Steel Production Plan
  3.5 Factory Assembly

- Section 4 SHIPPING PLAN

  4.1 Shipping Trade-Off
  4.2 Technical Feasibility of Airshipping
  4.3 Airshipping Cost Assessment

- Section 5 INSTALLATION PLAN

  5.1 Site Preparation
  5.2 Foundation Installation
  5.3 Site Assembly

- Section 6 OPERATIONS AND MAINTENANCE

  6.1 Operations
  6.2 Scheduled Maintenance
  6.3 Unscheduled Maintenance

Section 7 presents the cost scaling results and Section 8 discusses recommendations for cost reduction. Three appendices provide the detail backup for the installation cost element.